

Corn-Residue Transformations into Root and Soil Carbon as Related to Nitrogen, Tillage, and Stover Management

R. R. Allmaras, D. R. Linden, and C. E. Clapp*

ABSTRACT

Soil organic carbon (SOC) is sensitive to management of tillage, residue (stover) harvest, and N fertilization in corn (*Zea mays* L.), but little is known about associated root biomass including rhizodeposition. Natural C isotope abundance ($\delta^{13}\text{C}$) and total C content, measured in paired plots of stover harvest and return were used to estimate corn-derived SOC (cdSOC) and the contribution of nonharvestable biomass (crown, roots, and rhizodeposits) to the SOC pool. Rhizodeposition was estimated for each treatment in a factorial of three tillage treatments (moldboard, MB; chisel, CH; and no-till, NT), two N fertilizer rates (200 and 0 kg N ha⁻¹), and two corn residue managements. Treatments influenced cdSOC across a wide range (6.8–17.8 Mg C ha⁻¹). Nitrogen fertilization increased stover C by 20%, cdSOC by only 1.9 Mg C ha⁻¹, and increased rhizodeposition by at least 110% compared with that with no N fertilizer. Stover harvest vs. stover return reduced total source carbon (SC) by 20%, cdSOC by 35%, and total SOC. The amount of stover source carbon (^sSC) responded to tillage (MB > CH > NT), but tillage affected the amount of cdSOC differently (NT > CH > MB). Total SOC was maintained only by both N fertilization and stover return during the 13-yr period. The ratio of SC in the nonharvestable biomass to ^sSC ranged from 1.01 to 3.49; a ratio of 0.6 conforms to a root-to-shoot ratio of 0.4 when the root biomass includes 50% rhizodeposits. Tillage controlled the fraction of SC retained as cdSOC (i.e., humified; 0.26 for NT and 0.11 for MB and CH), even though N fertilization, stover harvest, and tillage all significantly influenced SC. Decomposition of labile rhizodeposits was a major component of the nonhumified fraction. Rhizodeposition was as much as three times greater than suggested by laboratory and other controlled studies. To understand and manage the entire C cycle, roots and rhizodeposition must be included in the analysis at the field level.

TILLAGE GREATLY INFLUENCES SOC storage (Angers et al., 1995; Reeves et al., 1997; Dao, 1998; Needelman et al., 1999; Clapp et al., 2000). Storage of SOC in soil depths <7.5 cm is usually greater with no-tillage than in annually tilled systems when sweep, CH, disc, or MB are used for the primary tillage operation (Allmaras et al., 2000). However, SOC storage below 7.5 cm can be greater in annually tilled systems (Jastrow, 1996; Clapp et al., 2000). Depth distribution of SOC has been linked to tillage tool control over the burial depth of crop residues (Allmaras et al., 1988). Numerous factors interact with tillage to influence changes in SOC storage, such as soil texture and sampling depth (Ellert and Bettany, 1995), time since treatments were initiated (Liang et al., 1998), and N fertilizer rate and placement (Gregorich et al., 1995, 1996; Wanniarachchi et al., 1999).

Recent studies of SOC storage and turnover have employed ¹³C natural abundance ($\delta^{13}\text{C}$) as an in situ marker of relic and recent SOC pools. Mass concentrations of SOC and the $\delta^{13}\text{C}$ signature are sufficient to calculate the amount of SOC originating from a C₄ crop (e.g., corn) or from a C₃ crop [e.g., soybean, *Glycine max* (L.) Merr.] when the initial soil organic carbon (SOC_i) has a different ¹³C signature than the current crop (Balesdent et al., 1987). The $\delta^{13}\text{C}$ technique has shown that tillage influences the depth distribution of SOC (Angers et al., 1995; Layese et al., 2002), storage of SOC stock (Balesdent et al., 1988, 1990), and CO₂ efflux from decomposing crop residue (Rochette et al., 1999a). Gregorich et al. (1996) reported significant SOC turnover as influenced by long-term N fertilization of continuous corn. Soil organic C and $\delta^{13}\text{C}$ measurements indicated that N fertilized soils contained more SOC from recent crops than unfertilized soils; the difference was accounted for by more C₄-derived C in fertilized soils (Gregorich et al., 1996). From 22 to 30% of the remaining total SOC in the Ap horizon was replaced by cdSOC in fertilized soils, whereas in unfertilized soil, only 15 to 20% was replaced during a 30-yr period. The $\delta^{13}\text{C}$ technique has allowed recent-crop inputs to the total SOC pool to be quantified as caused by differences in soil management, even though the total SOC pool itself may decrease, increase, or not change during the recent-crop period.

Many factors are known to influence the quantity of C retained by the soil, including mass of C inputs (Buyanovsky and Wagner, 1997; Huggins et al., 1998), initial amount of SOC (Campbell et al., 1991), soil texture (Needelman et al., 1999), soil temperature and water regimes (Rendig and Taylor, 1989; Kaspar and Bland, 1992; Goss and Watson, 2003), soil N content (Gregorich et al., 1996), fertilizer applications (Balanane and Balesdent, 1992), crop residue contact with soil (Clapp et al., 2000), composition of the residue C source (Martens, 2000), and the presence of living roots (Cheng and Coleman, 1990). Measurement problems may also influence the quantity of C retained, such as uncertainty in the conversion from specific mass concentrations to a volumetric or field area basis because of incomplete sampling depth and bulk density determination (Ellert and Bettany, 1995) and unspecified spatial

USDA-ARS, Dep. of Soil, Water, and Climate, Univ. of Minnesota, St. Paul, MN 55108. Received 9 June 2003. *Corresponding author (ecclapp@umn.edu).

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: $\delta^{13}\text{C}$, ¹³C natural abundance; cdSOC, corn-derived soil organic carbon; CH, chisel plow; *f*, fraction of soil organic carbon derived from corn; *F*, ratio of ^scdSOC to total C in stover; *h*, residues harvested; HI, harvest index; MB, moldboard plow; NT, no-tillage; *R*, ratio of ^uSC to ^sSC; *r*, residues returned; ^s, stover as a portion of SOC or cdSOC; SC, source carbon for input to soil; SOC, soil organic carbon; SOC_i, initial soil organic carbon; SOC_r, relic soil organic carbon; SY, stover yield; ^u, unharvestable material as a portion of SC or cdSOC.

and temporal sampling variability (Veldkamp and Weitz, 1994).

Belowground deposition of fixed C in structural root biomass, exudates, mucilage, and sloughed cells may be a major source for SOC accumulation (Sauerbeck and Johnen, 1977; Balesdent and Balabane, 1992; Buyanovsky and Wagner, 1997; Bolinder et al., 1999; Bottner et al., 1999; Flessa et al., 2000) in the field, but a major limitation is that the contribution of rhizodeposits to SOC has not been directly measured in the field. Qian et al. (1997) and Bottner et al. (1999) have shown that the rhizosphere contains abundant labile C and N, which undoubtedly accelerates C mineralization. Structural root biomass has been measured (Buyanovsky and Wagner, 1997; Huggins and Fuchs, 1997), but errors arise because the amount of fine structural-root biomass lost during root washing is most often not specified or measured.

The ratio of root-to-shoot biomass expressed as a proportion is needed to estimate and compare belowground biomass, including root exudates and other rhizodeposits, as a function of shoot biomass including grain. With only measured structural root biomass, Huggins and Fuchs (1997) calculated a root-to-shoot ratio of 0.25 for corn, while Buyanovsky and Wagner (1997) measured ratios of 0.28, 0.21, and 0.23 for wheat (*Triticum aestivum* L.), corn, and soybean, respectively, at harvest. Buyanovsky and Wagner (1997) also reported that the root-to-shoot (vegetative + grain) ratios were 0.48, 0.35, and 0.38 for wheat, corn, and soybean, respectively, when the rhizodeposits were included. Bolinder et al. (1999) assembled a mean root-to-shoot ratio of 0.19 for corn when considering only plant biomass (vegetative + grain) and suggested a ratio of 0.38 when the belowground SC included an equal biomass proportion of root mass and rhizodeposits. Whipps (1985) also suggested rhizodeposits to be 45 to 60% of the total root-associated biomass. Another survey of the literature (Bolinder et al., 1999) includes a higher proportion of corn root residue (21%) incorporated into SOC compared with 12% retained from shoot. Balesdent and Balabane (1996) found that roots contributed 1.5 times more C to SOC than the shoot in a direct field study with MB tillage and moderate N supply. However, root-to-shoot ratios and relative contributions to SOC have not been adequately field-measured to evaluate the relative effects of tillage, residue management, and N fertilization.

There is current national interest to harvest corn stover for biofuel (Mann et al., 2002; Wilhelm et al., 2004), but such an intensive removal of corn stover may produce a significant loss of SOC, reduce soil aggregation, and accelerate runoff and soil erosion. Wilhelm et al. (2004) reviewed corn stover harvest impacts on corn biomass production, sequestered SOC (loss or gain), belowground biomass (structural root + rhizodeposit), and retention of soil organic matter.

Clapp et al. (2000) summarized SOC and ^{13}C abundance in a factorial field experiment with three tillage treatments, two residue (stover) managements, and two N levels after 13 yr of continuous corn. The objective

of this additional study was to evaluate a new method to estimate corn C that is incorporated belowground into unharvestable root and associated rhizodeposits. For this model, paired plots of harvested and unharvested stover were required. Model results allow the impacts of tillage, N, and residue management on the retention of plant C in SOC to be evaluated, and provide estimates of the amount of rhizodeposition and corresponding C released during mineralization (decomposition). A secondary objective was to show that corn stover harvest for biofuel or silage may significantly influence SOC dynamics and reduce cdSOC.

MATERIALS AND METHODS

Field Experiment and Original Parameters

Field data and related laboratory analyses were obtained from a field experiment initiated in 1980 at the University of Minnesota Research and Outreach Center, Rosemount, MN (Clapp et al., 2000; Linden et al., 2000). The soil is a Waukegan silt loam (fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludoll), formed from a silt loam loess (about 50 to 80 cm thick), and underlain by neutral to calcareous glacial outwash sand and gravel. The experiment consisted of a factorial arrangement with three tillage treatments, two crop residue (stover) management practices, and two N fertilization treatments in a continuous corn production system. The experimental design was a modified split plot with tillage \times residue management as main plots and N treatments (four replications in each main plot) as subplots. Details of the experimental design and procedures are reported by Clapp et al. (2000) and Linden et al. (2000).

Briefly, the primary tillage treatments in the fall after harvest and chopping of stalks were NT, MB, and CH, with no secondary tillage or post-plant cultivation, which is an unusual management. Primary tillage depths were 25 and 17 cm for MB and CH, respectively. Residue treatments were corn stover returned (*r*) and corn stover harvested (*h*), with the grain always being harvested. The crown, including all exposed brace roots, was not included in the stover harvest, but was included as part of the root biomass. However, crown incorporation ranged from very little with NT to complete with MB tillage; nearly complete incorporation was achieved with CH tillage. Nitrogen, surface broadcast as ammonium sulfate $[(\text{NH}_4)_2\text{SO}_4]$ in the spring at 200 kg N ha^{-1} without incorporation, was compared with a zero N control. Grain yield and stover yield (SY) were measured annually for 13 yr (Linden et al., 2000). Soil samples, taken from 0- to 15- and 15- to 30-cm depth increments at 2- to 3-yr intervals, were analyzed for total SOC and $\delta^{13}\text{C}$ (Clapp et al., 2000). Soil organic C on a volume basis was calculated with measured mass fractions of C, and soil bulk density measured gravimetrically in the same soil cores. Yields (both stover and grain), total SOC, and $\delta^{13}\text{C}$ were presented as functions of time for each of the 12 treatment combinations.

The $\delta^{13}\text{C}$ values, from the proportional-ratio procedure (Clapp et al., 2000), provided an estimate of the fraction of the SOC that was corn-derived for each treatment:

$$\delta^{13}\text{C}_m = f \times \delta^{13}\text{C}_a + (1 - f) \delta^{13}\text{C}_b, \quad [1]$$

where $\delta^{13}\text{C}_m$ is the final $\delta^{13}\text{C}$ in the SOC, f is the fraction of SOC from corn, $\delta^{13}\text{C}_a$ is the $\delta^{13}\text{C}$ from corn residue (-12‰ ; Huggins et al., 1998), and $\delta^{13}\text{C}_b$ is the initial $\delta^{13}\text{C}$ in SOC. This fraction (f) multiplied by the final SOC estimated the cdSOC:

$$\text{cdSOC} = f \text{ SOC}. \quad [2]$$

The total C available from stover was estimated as the accumulated yield (Linden et al., 2000) with an average C content of 420 g kg⁻¹ (Clapp et al., 2000). The final SY estimates did not include Year 13 because SOC had already been determined on samples in the spring and early summer of the same year.

Theory and New Parameters

A new model approach was developed to estimate the unharvestable corn C as a component of the SOC pool. This approach required the corn stover return (*r*) treatment to be paired with that subjected to stover harvest (*h*). Briefly, in Step 1, cdSOC in the *h* treatment estimates the portion of the cdSOC in the belowground (unharvestable) C in the *h* treatment. In Step 2, the cdSOC due to stover in the *r* treatment was obtained by subtracting out the cdSOC estimated in Step 1 from the total cdSOC. In Step 3, the ratio of SY was assumed to represent the ratio between the cdSOC from the unharvestables in the *r* and *h* treatments. Equations [3] to [5] detail the partitioning of cdSOC, and Eq. [6] to [8] derive the unharvestable source carbon (^uSC).

Total SOC and δ¹³C, determined at 2- to 3-yr intervals, during 13 yr of continuous treatments, were aligned by year so that harvest data preceded the year when soil was sampled for SOC and δ¹³C. Soil was sampled within about 6 wk after seeding. Because of timing differences, some adjustments of the original SOC and cdSOC presented by Clapp et al. (2000) were required. Data were aligned separately under each primary tillage treatment to define cdSOC as a function of the SC left after harvest of grain or grain plus stover because tillage treatments were not all sampled at the same 2- to 3-yr schedule. Thus, both *h* and *r* treatments under each of the tillage × N treatments were combined (six separate combinations) into a single relationship even though they differed in total SC.

This paired-plot analysis used estimated changes in SOC and δ¹³C from the beginning to the end of the 13-yr experimental period. Initially, the soil had a strong C₃-labeled SOC fraction partially because of the prior production of C₃ crops. Initial, internal, and final values of SOC and δ¹³C as a function of time were reanalyzed because of soil sampling adjustments with respect to harvest. Statistically significant linear regressions as a function of time were used to estimate interior and end points except when there were nonlinear trends of SOC and δ¹³C as functions of time. When regressions were not statistically significant and there was evidence of linearity as a function of time, a nearly linear relation was estimated manually to determine interior and endpoints of SOC and δ¹³C. Most functions of time were significantly (*P* < 0.05) linear. For the 15- to 30-cm layer of the MB treatment, δ¹³C was nonlinear and required the interior and end points to be estimated manually. A later discussion links this nonlinearity to soil inversion due to MB tillage. Linearity of SOC, δ¹³C, and SY as a time function permits linearity between these data and SC.

In the *h* treatments, the cdSOC was produced entirely from the unharvestable material (crown, root, and rhizodeposits) remaining after harvest of both grain and stover (Step 1):

$$^u\text{cdSOC}_h = \text{cdSOC}_h, \quad [3]$$

where ^ucdSOC_{*h*} is the cdSOC derived from the unharvestables and the subscript *h* refers to the residue harvested treatments. Rhizodeposits include exudates and sloughed root tissue within the rhizosphere.

In Step 2 the following relationship was assumed:

$$^s\text{cdSOC}_r = \text{cdSOC}_r - ^u\text{cdSOC}_h, \quad [4]$$

where ^scdSOC_{*r*} is the cdSOC from stover in the *r* treatment, cdSOC_{*r*} is the cdSOC measured in the *r* treatment, and ^ucdSOC_{*h*} is the unharvestables in the *h* treatment.

An assumption was made, somewhat similar to that of Bolinder et al. (1999), that the unharvestable cdSOC is nearly equivalent under the *h* and *r* treatments, differing only in proportion to the aboveground SYs for the respective treatments. This assumption can be made because stover harvest was carried out at the end of the growing season. This assumption also permits an estimate of the ^ucdSOC under the *r* treatment to be equal to the ^ucdSOC under the *h* treatment multiplied by the ratio of the SYs (Step 3):

$$^u\text{cdSOC}_r = (\text{SY}_r/\text{SY}_h) ^u\text{cdSOC}_h, \quad [5]$$

where SY is cumulative SY, the subscript *r* refers to the residue returned treatment, and other symbols are as previously defined. Equation [5] is based upon the assumption that any conditions that produce differences in the belowground (plus unharvestable crown) biomass between *h* and *r* treatments is also expressed in their respective SY.

Source C from stover is the product of total SY and average C content of 420 g kg⁻¹. The ratio (*F*) of ^scdSOC_{*r*} to the total C in stover,

$$F = ^s\text{cdSOC}_r / (0.42 \text{ SY}_r) = ^s\text{cdSOC}_r / ^s\text{SC}, \quad [6]$$

was then used to estimate the ^uSC,

$$^u\text{SC} = ^u\text{cdSOC}_r / F, \quad [7]$$

for each treatment.

For simplicity and the lack of any experimental evidence to the contrary, we assumed that the unharvestable material had the same C content as the stover and was equivalent to stover as a source for cdSOC. However, some research shows that root biomass in ^uSC is more resistant to decomposition than the biomass in ^sSC (Bolinder et al., 1999; Ehleringer et al., 2000; Wilhelm et al., 2004) and therefore contributes more C to cdSOC. Higher resistance to degradation of structural root biomass is somewhat counterbalanced by a more labile nature of root exudates and other rhizodeposits to mineralization (Qian et al., 1997; Bottner et al., 1999; Rochette et al., 1999a).

The total SC is the sum of ^uSC and ^sSC sources of C:

$$\text{SC} = ^u\text{SC} + ^s\text{SC} \quad [8]$$

The NT treatment provided a clear distinction of SOC components between the 0- to 15- and 15- to 30-cm depths because there was never any mechanical mixing. A ratio of *R* = ^uSC/^sSC could thus be indicated for each depth independently or merely summed for the 0- to 30-cm depth. This was not the case, however, for both the MB and CH treatments since there was soil mixing and differential residue burial between layers (Clapp et al., 2000). Consequently, the ratio for ^uSC to ^sSC for the CH and MB treatments were each derived from the sum over both depths. This ratio was also treated similarly for NT because no distinction can be made about the relative SY contribution to the two soil layers.

Field-measured parameters (δ¹³C, SOC, and SY) were determined by ANOVA and linear regression (SAS Institute, 1988) in the original data of the factorial (Clapp et al., 2000; Linden et al., 2000). Standard errors for these field-measured parameters were then used to approximate SEs of subsequent estimates (from Eq. [2] through [8]) by methods of Allmaras

and Kempthorne (2002). Standard errors are repeated when the estimates are discussed. The *t* test ($P < 0.05$) was used throughout for means separation.

RESULTS AND DISCUSSION

Stover Yields

Average annual SY ranged between 4.0 and 5.8 Mg ha⁻¹. Accumulated SY as a function of time for each treatment in the 13-yr experiment were presented by Linden et al. (2000), and the 12-yr total SY are shown in Tables 1, 2, and 3 for NT, MB, and CH treatments, respectively, with a SE of 0.70 Mg biomass ha⁻¹ and 36 df. Linden et al. (2000) showed no differences in SY trends over time due to tillage during the first 5 yr, but significant ($P < 0.05$) SY differences between treatments over time began to appear after 5 yr. The slopes of the time series remained consistent through Year 13. Stover yields under NT remained lower than under MB in all treatments. Yield was significantly ($P < 0.05$) higher in all treatments other than when stover was returned and fertilizer was applied at 200 kg N ha⁻¹. Except when stover was returned and 200 kg N ha⁻¹ was applied, SY under CH was significantly ($P < 0.05$) higher than in NT treatments. There were statistically significant linear trends with *r*² values > 0.90 for accumulated SY as a function of time for all treatments (Linden et al., 2000). Therefore, regression results suggest that subsequent analyses of SOC and $\delta^{13}\text{C}$ changes can be expressed as linear functions of stover C and total SC.

The mean annual aboveground net primary production, computed with a mean harvest index (HI) of 0.56 ± 0.16 (Linden et al., 2000), ranged from 4.1 to 5.6 Mg C

ha⁻¹, depending on the treatment combination. These ranges of HI are also indicative of interannual variation of the hydrothermal environment, and are similar to Brye et al. (2002) who estimated 8.0 Mg C ha⁻¹ yr⁻¹ aboveground phytomass in a continuous corn experiment in south-central Wisconsin.

Total Soil Organic Carbon

Total SOC in the 0- to 30-cm depth ranged from 81 to 106 Mg C ha⁻¹ and were significantly ($P < 0.05$) larger in the combined *r* and 200 kg N ha⁻¹ treatment than in the other management treatments within each tillage treatment (i.e., a mean of 101.2 compared with 80.0 Mg C ha⁻¹; Tables 1, 2, and 3). This difference of total SOC between the combined *r* and 200 kg N ha⁻¹ vs. the other treatments was greatest in the NT treatment and least in the MB treatment. The mean SOC_i of 96 Mg C ha⁻¹ (Table 4) was taken from Clapp et al. (2000). The change in total SOC (ΔSOC) represented as a gain (Table 4) was positive when stover was returned and 200 kg N ha⁻¹ was applied in all three tillage treatments; ΔSOC was negative or nearly zero under the other combinations of stover management and fertilization in all three tillage treatments. The MB tillage produced the smallest annual change of ΔSOC , while the ΔSOC gain ranged from 0.7 to 1.5 Mg C ha⁻¹ within the 30-cm layer. When considered as management changes, the impacts of N fertilization and stover harvest on ΔSOC were as much as 10-fold larger than the 57 g C m⁻² yr⁻¹ associated with a conversion from conventional- to no-tillage or a smaller change associated with crop rotation (West and Post, 2002).

Table 1. Input and computed parameters used to estimate unharvestable and total-source carbon under no-tillage.

Depth	SY†	SOC‡	<i>f</i> §	cdSOC¶	^u cdSOC#	^s cdSOC††	<i>F</i> ‡‡	^u SC§§	<i>R</i> ¶¶	SC##
cm	Mg ha ⁻¹			Mg ha ⁻¹				Mg ha ⁻¹		Mg ha ⁻¹
	69.1			200 kg N ha ⁻¹ Residue return						
0–15		58.3	0.214	12.48	5.03	7.45	–†††	23.0	0.79	–
15–30		39.8	0.133	5.29	5.86	–0.57	–	22.4	0.77	–
0–30		98.1		17.77	10.89	6.88	0.24	45.4	1.56	74.4
	61.9			200 kg N ha ⁻¹ Residue harvest						
0–15		53.1	0.085	4.51	4.51	0	–	–	–	–
15–30		33.1	0.159	5.26	5.26	0	–	–	–	–
0–30		86.2		9.77	9.77	0	–	40.7	–	40.7
	52.1			0 kg N ha ⁻¹ Residue return						
0–15		48.0	0.166	7.97	4.67	3.30	–	14.2	0.64	–
15–30		33.2	0.195	6.47	2.64	3.83	–	8.0	0.36	–
0–30		81.2		14.44	7.31	7.13	0.33	22.2	1.01	44.1
	51.7			0 kg N ha ⁻¹ Residue harvest						
0–15		54.3	0.085	4.63	4.63	0	–	–	–	–
15–30		37.7	0.069	2.62	2.62	0	–	–	–	–
0–30		92.0		7.25	7.25	0	–	22.0	–	22.0
SE‡‡‡	0.70	0.10	0.027	1.00	1.00	1.00	0.03	0.3	0.37	11.0

† SY = stover yield. The ^sSC = stover source carbon assumed to be 0.42 (SY) with a SE of 0.30 Mg ha⁻¹.

‡ SOC = total soil organic carbon (final).

§ *f* = fraction of soil organic carbon derived from corn.

¶ cdSOC = carbon in total soil organic carbon derived from corn.

^ucdSOC = carbon in total soil organic carbon derived from unharvestables.

†† ^scdSOC = carbon in total soil organic carbon derived from stover.

‡‡ *F* = ^scdSOC/^sSC.

§§ ^uSC = unharvestable soil carbon.

¶¶ *R* = ^uSC/^sSC.

SC = total source carbon (input to soil).

††† No data.

‡‡‡ Applies only to the 0- to 30-cm layer unless otherwise indicated.

Table 2. Input and computed parameters used to estimate unharvestable and total-source carbon under moldboard plow tillage.

Depth	SY†	SOC‡	f§	cdSOC¶	^u cdSOC#	^s cdSOC††	F‡‡	^u SC§§	R¶¶	SC##
cm	Mg ha ⁻¹			Mg ha ⁻¹				Mg ha ⁻¹		Mg ha ⁻¹
	70.7			200 kg N ha ⁻¹ Residue return						
0–15		51.7	0.176	9.10	–†††	–	–	–	–	–
15–30		48.2	0.076	3.71	–	–	–	–	–	–
0–30		99.9		12.81	9.33	3.48	0.12	77.8	2.62	107.5
	67.8			200 kg N ha ⁻¹ Residue harvest						
0–15		48.4	0.185	8.95	–	–	–	–	–	–
15–30		48.0	0.001	0.00	–	–	–	–	–	–
0–30		96.4		8.95	8.95	0	–	74.6	–	74.6
	59.1			0 kg N ha ⁻¹ Residue return						
0–15		48.3	0.180	8.69	–	–	–	–	–	–
15–30		43.6	0.063	2.75	–	–	–	–	–	–
0–30		91.9	–	11.44	8.54	2.90	0.17	50.2	2.02	75.0
	60.4			0 kg N ha ⁻¹ Residue harvest						
0–15		46.6	0.155	7.22	–	–	–	–	–	–
15–30		45.8	0.003	1.51	–	–	–	–	–	–
0–30		92.4		8.73	8.73	0	–	51.4	–	51.4
SE‡‡‡	0.70	0.10	0.027	1.00	1.00	1.00	0.03	0.3	0.37	11.0

† SY = stover yield. The ^sSC = stover source carbon assumed to be 0.42 (SY) with a SE of 0.30 Mg ha⁻¹.

‡ SOC = total soil organic carbon (final).

§ f = fraction of soil organic carbon derived from corn.

¶ cdSOC = carbon in total soil organic carbon derived from corn.

^ucdSOC = carbon in total soil organic carbon derived from unharvestables.†† ^scdSOC = carbon in total soil organic carbon derived from stover.‡‡ F = ^scdSOC/^sSC.§§ ^uSC = unharvestable soil carbon.¶¶ R = ^uSC/^sSC.

SC = total source carbon (input to soil).

††† No data.

‡‡‡ Applies only to the 0- to 30-cm layer unless otherwise indicated.

Loss of SOC in the 0- to 30-cm depth during the 13-yr period averaged 4% of that initially present. This loss was small compared with the estimated 6% from a 40-cm profile in one season (Rochette et al., 1999b), and 27%

from a 1.4 m profile during a 4-yr period in a comparison of tillage and N fertilization (Brye et al., 2002). The absence of secondary tillage and no post-plant cultivation may partially explain the small loss from the SOC_i.

Table 3. Input and computed parameters used to estimate unharvestable and total-source carbon under chisel plow tillage.

Depth	SY†	SOC‡	f§	cdSOC¶	^u cdSOC#	^s cdSOC††	F‡‡	^u SC§§	R¶¶	SC##
cm	Mg ha ⁻¹			Mg ha ⁻¹				Mg ha ⁻¹		Mg ha ⁻¹
	69.9			200 kg N ha ⁻¹ Residue return						
0–15		60.0	0.179	10.74	–†††	–	–	–	–	–
15–30		45.6	0.023	1.05	–	–	–	–	–	–
0–30		105.6		11.79	9.23	2.56	0.09	102.6	3.49	132.0
	64.5			200 kg N ha ⁻¹ Residue harvest						
0–15		47.4	0.146	6.92	–	–	–	–	–	–
15–30		36.3	0.044	1.60	–	–	–	–	–	–
0–30		83.7		8.52	8.52	0	–	94.7	–	94.7
	56.3			0 kg N ha ⁻¹ Residue return						
0–15		54.6	0.148	8.08	–	–	–	–	–	–
15–30		42.2	0.044	1.86	–	–	–	–	–	–
0–30		96.8		9.94	6.85	3.09	0.13	52.7	2.23	76.2
	56.0			0 kg N ha ⁻¹ Residue harvest						
0–15		47.8	0.149	7.12	–	–	–	–	–	–
15–30		36.0	–0.008	–0.29	–	–	–	–	–	–
0–30		83.8		6.81	6.81	0	–	52.4	–	52.4
SE‡‡‡	0.70	0.10	0.027	1.00	1.00	1.00	0.03	0.3	0.37	11.0

† SY = stover yield. The ^sSC = stover source carbon assumed to be 0.42 (SY) with a SE of 0.30 Mg ha⁻¹.

‡ SOC = total soil organic carbon (final).

§ f = fraction of soil organic carbon derived from corn.

¶ cdSOC = carbon in total soil organic carbon derived from corn.

^ucdSOC = carbon in total soil organic carbon derived from unharvestables.†† ^scdSOC = carbon in total soil organic carbon derived from stover.‡‡ F = ^scdSOC/^sSC.§§ ^uSC = unharvestable soil carbon.¶¶ R = ^uSC/^sSC.

SC = total source carbon (input to soil).

††† No data.

‡‡‡ Applies only to the 0- to 30-cm layer unless otherwise indicated.

Table 4. Components of soil organic carbon (SOC), and annual inputs of source carbon (SC) to the 0- to 30-cm depth, and annual stover yield (SY) as influenced by tillage, stover management, and N fertilization.

Treatment†			Components of SOC‡				Annual SC§		Annual SY
Tillage	N rate	Stover mgt.	ΔSOC	cdSOC	SOC _R loss	Lost SC	§SC	Total SC	
	kg N ha ⁻¹		Mg C ha ⁻¹						Mg ha ⁻¹
NT	200	<i>r</i>	1.9	17.8	16.0	55.0	2.4	5.7	6.3
		<i>h</i>	-10.0	9.8	19.8	30.1	-	3.1	5.2
	0	<i>r</i>	-15.0	14.4	29.4	32.6	1.8	3.4	4.3
		<i>h</i>	-4.2	7.2	11.4	16.3	-	1.7	4.3
MB	200	<i>r</i>	3.6	12.8	9.2	95.7	2.5	8.3	5.9
		<i>h</i>	0.2	9.0	8.8	66.4	-	5.7	5.6
	0	<i>r</i>	-4.4	11.4	15.8	66.8	2.1	5.8	4.9
		<i>h</i>	-3.8	8.7	12.5	45.7	-	4.0	5.0
CH	200	<i>r</i>	9.4	11.8	2.4	117.5	2.4	10.2	5.8
		<i>h</i>	-12.6	8.5	21.1	84.3	-	7.3	5.4
	0	<i>r</i>	0.6	9.9	9.3	67.8	2.0	5.9	4.7
		<i>h</i>	-12.4	6.8	19.2	46.6	-	4.0	4.7
SE			1.2	1.0	1.9	12.0	0.02	0.9	0.06

† NT, no-tillage; MB, moldboard plow tillage; CH, chisel plow tillage; *r*, stover returned; *h*, stover harvested.

‡ cdSOC = corn-derived soil organic carbon; ΔSOC represented as a gain of SOC during 13-yr continuous corn; SOC_i = 96.25 ± 4.14 Mg C ha⁻¹ (mean ± SE); final SOC shown in Tables 1, 2, and 3; SOC_R loss = loss of relic SOC = SOC_i + ΔSOC - cdSOC; lost SC is the total source C not in the cdSOC.

§ Source carbon returned in both stover and unharvestable root; - indicates stover harvested.

δ¹³C Signature of Soil Organic Carbon and Corn-Derived Soil Organic Carbon

Values of δ¹³C, as functions of time, generally increased over time because of corn C (δ¹³C = -12‰), while the SOC_i had a mean δ¹³C signature of about -19‰, but different in the two soil layers (Clapp et al., 2000). These δ¹³C values had a SE of 0.15‰ with 32 df, as determined by linear regression over time, while the estimated SE of the *f* ratio was 0.027. The *r* treatments fertilized with 200 kg N ha⁻¹ had the highest biomass production (Tables 1, 2, and 3) and also produced the largest increase in δ¹³C over time (Clapp et al., 2000).

The SOC and δ¹³C values were combined to estimate cdSOC (Eq. [1] and [2]). The calculated *f* ratios were all positive and significantly (*P* < 0.05) greater than zero in the NT treatment (Table 1). Values of SOC and δ¹³C in the 0- to 15-cm depth were also significantly (*P* < 0.05) greater than zero in the MB (Table 2) and CH (Table 3) treatments. In the 15- to 30-cm layer, only two *f* values out of four were significantly (*P* < 0.05) greater than zero in the MB treatment and all *f* values were positive. In the 15- to 30-cm layer of the CH treatment, all *f* values were positive, except one that was negative and yet not different from zero. Both δ¹³C and SOC were stratified initially when the field experiment began in 1980. The 0- to 15-cm layer had a δ¹³C signature of -19.8‰ and 55.0 Mg SOC ha⁻¹, while the 15- to 30-cm layer had a δ¹³C signature of -18.0‰ and 40.4 Mg SOC ha⁻¹. During the first 4 yr (Fig. 1 and 2 in Clapp et al., 2000), it was estimated that the MB inversion moved about 8 to 15% of the original 0- to 15-cm layer into the 15- to 30-cm layer according to SOC and δ¹³C measurements. Some mixing in the CH treatment may also have occurred, especially if there was an occasional tillage tool penetration into the 15- to 30-cm layer. The final cdSOC values for the combined 0- to 30-cm depth after 13 yr ranged from 6.8 to 17.8 Mg C ha⁻¹. Final cdSOC values, obtained from the regression analysis to reduce variability, are shown in Tables 1, 2, and

3 for NT, MB, and CH treatments, respectively, and are summarized in Table 4. The estimated SE for final cdSOC was 1.0 Mg C ha⁻¹ with 32 df. Under the *h* treatments, cdSOC ranged between 50 to 75%, with an overall average of 65%, of the cdSOC under the *r* treatments. In a similar experiment comparing harvested to returned corn residue treatments, Balesdent and Balabane (1996) reported cdSOC for stover-harvested treatments to be 61% of that in stover-returned treatments. This large residue effect on cdSOC shows the adverse effects of corn stover harvest for biofuels. The mean effect of the *r* over the *h* treatment was 4.72 Mg C ha⁻¹. The mean effect of the 200 kg N ha⁻¹ rate on cdSOC compared with no N fertilization was 1.86 Mg C ha⁻¹ and was <50% of the stover-harvest effect. The mean cdSOC for NT, MB, and CH was 12.31, 10.44, and 9.26 Mg C ha⁻¹, respectively, with no interactions of tillage with N fertilization or residue management.

Source Carbon

Source C from SY (§SC) after 12 yr ranged from 21.7 to 29.0 Mg C ha⁻¹ and had a SE of 0.3 Mg C ha⁻¹ with 36 df (Tables 1, 2, and 3). Nitrogen fertilization significantly (*P* < 0.05) increased §SC from 23.5 with no N to 28.3 Mg C ha⁻¹ with the 200 kg N ha⁻¹ rate. Source C from SY was 24.7, 27.1, and 25.9 Mg C ha⁻¹ for the NT, MB, and CH treatments, respectively. Corn stover harvest significantly (*P* < 0.05) reduced the §SC from 26.4 to 25.3 Mg C ha⁻¹. There was a significant (*P* < 0.05) positive interaction of 2.3 Mg C ha⁻¹ between N fertilization and stover return influences on §SC.

Total SC for *h* treatments ranged from 22 to 95 Mg C ha⁻¹, while that for *r* treatments ranged from 44 to 132 Mg C ha⁻¹. The SE for total SC was approximately 11 Mg C ha⁻¹ with 32 df. Total SC under the treatments receiving 200 kg N ha⁻¹ were at least 40% greater than under the zero N control. The values of 1.7 to 10.2 Mg C ha⁻¹ yr⁻¹ (Table 4) had a wider range than other research reports for annual inputs of corn C (Balesdent

and Balabane, 1992, 1996; Bolinder et al., 1999). The SC for root + rhizodeposits explains part of the larger upper range.

Paired analysis of the r and h treatments provided estimates of the ratios: $F = {}^{\text{cd}}\text{SOC}/{}^{\text{s}}\text{SC}$ and $R = {}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ (Tables 1, 2, and 3). The F ratio is a measure of the efficiency of the SC in stover to be incorporated into the cdSOC. All F ratios were significantly ($P < 0.05$) smaller for the 200 kg N ha⁻¹ rate (0.15) than for no N fertilizer (0.21). In all six comparisons, the F ratio for NT (0.28) was significantly ($P < 0.05$) larger than that for the tilled (MB and CH) treatments (0.13). Each F ratio in Tables 1, 2, and 3 had an estimated SE of 0.03, based on 32 df.

The R ratio for the r treatment ranged from 1.01 to 3.49 with a SE of 0.37 (32 df; Tables 1, 2, and 3). The R ratios are not shown for the h treatment, but can be assumed to be similar to that for the r counterpart because the harvested stover source was an integral part of the plant throughout the growing season before harvest. With N fertilization, the R ratio for NT was 1.56, while that for tilled systems (MB and CH) averaged 3.04. Without N fertilization, the R ratio ranged from 1.01 to 2.23 for NT and tilled systems, respectively. Averaged across all other treatments, the R ratio for the 200 kg N ha⁻¹ rate was 2.84 and was 1.75 for the nonfertilized treatments. The significance of the R ratio is that as the ratio increases the amount of root + rhizodeposition produced also increases.

The R ratio confirms that N fertilization stimulated rhizodeposition because Huggins and Fuchs (1997) showed that structural corn root biomass itself, including the crown, did not respond to N fertilizer rates ranging from 16 to 195 kg N ha⁻¹. The larger $R = {}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ in the tilled (MB and CH) treatments compared with NT is likely due to more root tissue as shown by: (i) a greater depth and proliferation intensity of rooting as noted in the $\delta^{13}\text{C}$ profile (Layese et al., 2002); (ii) a greater lateral spread of small grain roots at a shallow depth in direct-drill compared with deeper roots in MB tillage (Drew and Saker, 1980); (iii) decreased corn and soybean root-length densities in NT compared with MB tillage (Voorhees, 1989); and (iv) less rooting in the upper 30 cm of NT compared with other reduced-tillage systems (Kaspar et al., 1991).

Clapp et al. (2000) estimated C returned in the root residue using shoot biomass, a HI value of 0.45, and a root-to-shoot biomass ratio of 0.22. A mean ${}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ (R) of 0.40 would have been required with no measured effect of tillage or N fertilization to match the root-to-shoot biomass ratio of 0.22. This root-to-shoot biomass ratio is nearly the same as determined by Huggins and Fuchs (1997), considering only recovery of structural root biomass. The range of ${}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ from 1.01 to 3.49 (Tables 1, 2, and 3) corresponded to root-to-shoot biomass ratios ranging from 0.26 with no N in NT to 1.53 with 200 kg N ha⁻¹ in CH. For instance, with 200 kg N ha⁻¹, the root-to-shoot biomass ratio for NT was 0.69, while the mean for tilled (MB and CH) systems was 1.46. These are both higher than the suggested 0.38 ratio, which included the 50% rhizodeposit plus the 50%

root biomass (Bolinder et al., 1999). The ${}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ ratio for CH with no N was 2.23 with a root-to-shoot biomass ratio of 0.98. This ratio is unusually larger than for the other tillage systems with no N fertilization, yet a simulation (Molina et al., 2001) applied to this treatment predicted an approximate ${}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ ratio of 1.8 (i.e., a root-to-shoot ratio of 0.8). From a similar-type field experiment, Balesdent and Balabane (1996) obtained an ${}^{\text{u}}\text{SC}/{}^{\text{s}}\text{SC}$ ratio of 1.6, indicating a significant amount of rhizodeposition.

Considerable literature based upon laboratory measurements and field modeling supports root exudates or other rhizodeposits as major C sources to SOC (Sauerbeck and Johnen, 1977; Whipps, 1985; Bolinder et al., 1999; Bottner et al., 1999; Molina et al., 2001). Therefore, future C studies on rhizodeposition need considerably more data on SOC and its components, rather than assumptions based solely on aboveground measurements, to provide the most realistic estimates of the contribution of C from rhizodeposition to the total SOC.

A negative correlation and somewhat nonlinear relation (not shown) between the R and F ratios (Tables 1, 2, and 3) suggests that ${}^{\text{u}}\text{SC}$ suppresses ${}^{\text{s}}\text{cdSOC}$, but at high F ratios the influence decreases. A possible interpretation of the negative relation is that some root C may be more resistant to decomposition as suggested earlier (Bolinder et al., 1999; Bottner et al., 1999; Wilhelm et al., 2004), but for this study it was assumed that stover and unharvestable roots, including rhizodeposits, were equivalent as a C source to cdSOC. Perhaps similar paired residue management field studies with other agronomic crops may explain the dilemma. Modeling with modified R and F ratios may also be helpful.

Corn-Derived Soil Organic Carbon as a Function of Source Carbon

Both cdSOC and total SC were estimated relative to stover harvest, tillage systems, and N application rate (Tables 1, 2, and 3). Fit to a zero intercept, cdSOC increased at a rate of 0.26 Mg ha⁻¹ as SC increased in the NT treatment, but cdSOC only increased at the rate of 0.11 Mg ha⁻¹ as SC increased in the MB and CH treatments combined (Fig. 1). These small slopes, even though significantly ($P < 0.01$) different from each other, indicate a major partition between humified SOC and a rhizodeposition labile to C mineralization as related to tillage treatments. Within each tillage system, the r treatment generally had the largest SC, and within each residue-harvest management practice the 200 kg N ha⁻¹ treatment had a larger SC than the zero N control. The scatter of points with +N compared with those with zero N within a tillage system (Fig. 1) suggests that N reduces the efficiency for conversion of SC to cdSOC. Pulse labeling with $^{14}\text{CO}_2$ showed an immediate CO_2 efflux indicative that >60% of the root biomass consists of rhizodeposition (Swinnen et al., 1994; Kuzyakov, 2002). Humification rates of 11 and 26% due to tillage treatment are similar to literature estimates: 23% (Angers et al., 1995); 30% (Gregorich et al., 1995); 15%

(Balesdent and Balabane, 1996); 17% (Bolinder et al., 1999); and 31% (Flessa et al., 2000). However, all of these studies, except Balesdent and Balabane (1996), required literature-based guidelines to estimate the belowground C by a root-to-shoot ratio.

The humification estimates of 11% for MB and CH tillage are also smaller than the estimates of 21 to 26% given by Clapp et al. (2000) when stover was returned and an empirical root-to-shoot ratio was used. Increases of this ratio to the 70% range when stover was harvested (Clapp et al., 2000) indicates an underestimation of the root-to-shoot ratio.

Components of Soil Organic Carbon and Source Carbon Inputs

Components of SOC and SC inputs are listed together in Table 4 to account for SOC lost to CO₂ efflux. Four components of SOC (Table 4) measured in the original field experiment were used to estimate the unharvestable root biomass in our model. A comparison of ΔSOC and cdSOC provides a different conclusion about SOC sequestration relative to the 12 management combinations. The cdSOC response to the four N fertilization and stover management treatment combinations is consistently related to the supply of corn biomass within each tillage treatment. However, ΔSOC within and between tillage treatments does not follow the same pattern as cdSOC.

Decomposition of relic SOC (SOC_R) and current SC were both related to stover residue management and associated N fertilization. The three tillage systems (NT, MB, CH) each produced a different degree of stover burial (and the crown component of the unharvestable root), as well as different degrees of fertilizer-residue contact produced by N fertilizer application in spring without incorporation (Clapp et al., 2000). Interannually different hydrothermal environments may have also influenced ΔSOC as related to both tillage and N fertilization (Linden et al., 2000). The four soil management combinations produced smaller ΔSOC effects in the MB than in the NT and CH tillage treatments, possibly because all crop residue was buried and separated from applied N. Except for the 29.4 Mg C ha⁻¹ loss of SOC_R with stover returned and no N fertilization in the NT treatment, the mean SOC_R losses did not differ among tillage treatments. Large surface accumulations of undecomposed stover and crown biomass with a high C-to-N ratio in the absence of N explains both the large negative ΔSOC and the large SOC_R loss compared with a small gain in the same residue management practice in the presence of applied N. Brye et al. (2002) showed significant interannual hydrothermal environments, but concluded that SOC dynamics were more sensitive to tillage and N fertilization management practices.

A lost SC is listed (Table 4) as the SC fraction not included in cdSOC (Fig. 1). There was a significantly ($P < 0.05$) larger amount of lost SC under CH and MB compared with NT because the tilled treatments produced more total SC than did NT, but retained proportionately less humified SOC. The mean annual po-

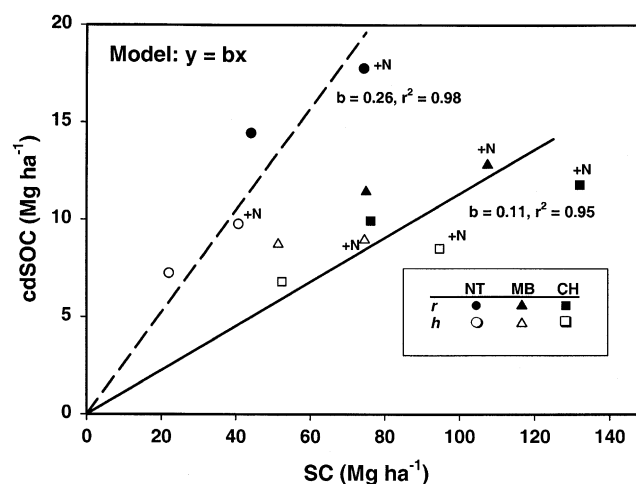


Fig. 1. Corn-derived soil organic carbon (cdSOC) as a function of source carbon (SC) produced by treatments of tillage (no-till, NT; moldboard, MB; chisel, CH), N fertilization (0 and 200 kg N ha⁻¹, indicated by +N data point labels), and stover management [residues harvested (*h*) and residues returned (*r*)]. The *F* values for regression were significant at a $P < 0.01$. Regression lines are dashed for NT and solid for combined MB and CH tillage treatments.

tential for C mineralization from SOC_R loss and lost SC to CO₂ efflux ranged from 1.4 to 10.0 Mg C ha⁻¹, depending on treatment combination. Mean annual potential for the three tillage treatments when there was a gain of ΔSOC was 4.6, 8.0, and 9.8 Mg C ha⁻¹ for the NT, MB, and CH treatments, respectively. These lost SC estimates are within the range of total seasonal CO₂ efflux measured in corn production studies. Field-measured seasonal total CO₂ efflux values were about 10 Mg C ha⁻¹ during 4 yr of continuous corn (Brye et al., 2002); 7.5 Mg C ha⁻¹ during corn production after wheat (Rochette et al., 1999a); 6.5 Mg C ha⁻¹ during barley (*Hordeum vulgare* L.) production after corn (Rochette et al., 1999b), and 4.2 Mg C ha⁻¹ during corn production (Rochette and Flanagan, 1997).

Total SC values were significantly ($P < 0.05$) influenced by tillage treatment even though ^sSC values were not different among tillage treatments (Table 4). A mean annual corn SY production of 5.8 to 6.3 Mg ha⁻¹, obtained with high N fertilization and stover return, was required to maintain a positive ΔSOC. This estimate is similar to other estimates for the northern Corn Belt: 5.6 Mg ha⁻¹ (Huggins et al., 1998) and 5.0 Mg ha⁻¹ (Kucharik et al., 2001).

SUMMARY AND CONCLUSIONS

An analysis of paired residue-harvest and residue-returned treatments in our model was applied to the original data of Clapp et al. (2000), in which there was a factorial arrangement of three tillage, two N rate, and two residue-return treatments. This analysis allowed estimates of ^sSC, SOC, *f*, total cdSOC, and cdSOC derived from unharvestable biomass (^uSC; including structural root biomass plus rhizodeposits). The impact of each treatment on the above C dynamics was estimated in a silt loam with moderate to high initial mineralizable N.

Applied N (200 kg N ha^{-1}) increased ^sSC as much as 4.8 Mg C ha^{-1} , 20% greater compared with a zero N control, and increased cdSOC by 1.9 Mg C ha^{-1} within the overall range of cdSOC from 6.8 to $17.8 \text{ Mg C ha}^{-1}$. The $^s\text{cdSOC}/^s\text{SC}$ ratio indicated that the 200 kg N ha^{-1} rate was less efficient than no fertilization in converting SC to cdSOC , and N application produced a $^u\text{SC}/^s\text{SC}$ ratio at least 110% larger than without fertilizer, which is indicative of more rhizodeposition.

Stover harvest reduced cdSOC by 35% from the $4.72 \text{ Mg C ha}^{-1}$ produced by stover return, and reduced SC to 60% of that when stover was returned. Corn stover return combined with N fertilization was the only combination to prevent loss of total SOC and tillage had no significant effect as long as this combined input was applied.

Stover-derived SC response to tillage was $\text{MB} > \text{CH} > \text{NT}$, yet the order of cdSOC was $\text{NT} > \text{CH} > \text{MB}$. The $^s\text{cdSOC}/^s\text{SC}$ ratio was greater for NT (0.28) than the tilled (MB and CH) treatments (0.13), which partially explains the more efficient overall humification under NT.

The relative amount of rhizodeposition increased as the ratio $^u\text{SC}/^s\text{SC}$ increased from 1.01 to 3.49. When fertilized with N, this ratio was 1.56 for NT and 3.04 for the tilled (MB and CH) systems; without N fertilization, this ratio varied from 1.01 to 2.23. Hence, rhizodeposition increased as N was applied or when there was tillage in the system. A $^u\text{SC}/^s\text{SC}$ ratio of 0.6 is large enough for a root-to-shoot ratio that includes an equal content of structural root biomass and rhizodeposition.

Total source C transformation to cdSOC indicated a humification fraction of 0.26 in NT, while the tilled (MB and CH) systems had a lower fraction (0.11). Lower fractions are indicative of the ephemeral nature of rhizodeposits. This paired (stover harvest vs. return) analysis from field measurements shows a significant treatment effect on rhizosphere C that exceeds most controlled laboratory estimates by at least 80%. This large rhizodeposition associated with measured losses of SOC and SC together was within 25% of the seasonal CO_2 efflux total measured by others in corn field experiments.

An advanced understanding of C sequestration requires better field measurement and assessment of the C cycle dynamics in the root and rhizosphere, as well as humification and CO_2 efflux. Field measurement also requires a more accurate accounting of the various C pools, including root C, related to actual field management of the agroecosystem.

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